MULTIMEDIA UNIVERSITY

STUDENT ID NO

MULTIMEDIA UNIVERSITY

FINAL EXAMINATION

TRIMESTER 2, 2015/2016

EMF4086 – RF TRANSISTOR CIRCUIT DESIGN

(ALL SECTIONS)

4 MARCH 2016
3:00 p.m. – 5:00 p.m.
(2 Hours)

INSTRUCTIONS TO STUDENTS

1. This question paper consists of 19 pages with 4 questions only.
2. Answer **ALL** questions. All questions carry equal marks of 25. The distribution of the marks for each question is given.
3. Please print all your answers in the Answer Booklet provided.

Question 1

(a) An engineer is tasked to design a small-signal low-noise transistor amplifier operating at 2.4 GHz, with the following characteristics:
Supply voltage: 3.3 V.
I_C current: Not more than 15 mA.
Power gain (G_P): At least 10 dB.
Noise Figure: Not more than 1.5 dB.

A selection of RF transistors are shown in Appendix 1, with the relevant pages of the datasheets attached. Select a suitable transistor for the job. Note that BFP420 is a Silicon-Germanium hetero-junction transistor (HBT), with typical $V_{BE(ON)}$ of 0.5V, while BFG425W and BFR520 are Silicon transistors with typical $V_{BE(ON)}$ of 0.75V.
Hint: Compare each transistor parameters with the requirements above. You will need to make some engineering judgments as certain parameters are provided at 1.8 and 2.0 GHz in the datasheets,

[11 marks]

(b) Propose a suitable V_{CE} and I_C for you chosen transistor based on the information from part (a), and proceed to design a **practical** biasing network using RLC components for the transistor, assuming 50Ω source and load impedance. Provide a sketch of the complete schematic.
Hint: you can use Emitter Feedback, Collector Feedback, Base Feedback network or any suitable configuration, supported with reasonable assertions.

[14 marks]

Question 2

The schematic of an RF amplifier using BFR92A transistor designated for operation at 900 MHz is shown in Figure Q2A. The corresponding small-signal S-parameters, Constant Power Gain (G_P), Constant Available Power (G_A) and Constant Noise Figure circles are shown in Figure Q2B.

(a) Perform a stability test at 900 MHz using the Rollett Stability Factor and comment on the allowable source and load impedance.

[7 marks]

(b) Determine the theoretical maximum transducer power gain (G_T) that can be obtained from this circuit in dB.

[4 marks]

(c) Based on the data presented in Figure Q2B, suggest a pair of source and load impedance for this amplifier to obtain at least 11 dB of transducer power gain and not more than 1.5 dB of noise figure
Hint: You can use either Constant G_P or Constant G_A circles approach. Also using real impedance is easier in terms of conversion between reflection coefficient and impedance.

[10 marks]

Continued...

(d) Suggest ONE (1) method to increase the transducer power gain further without affecting the noise figure.

[4 marks]

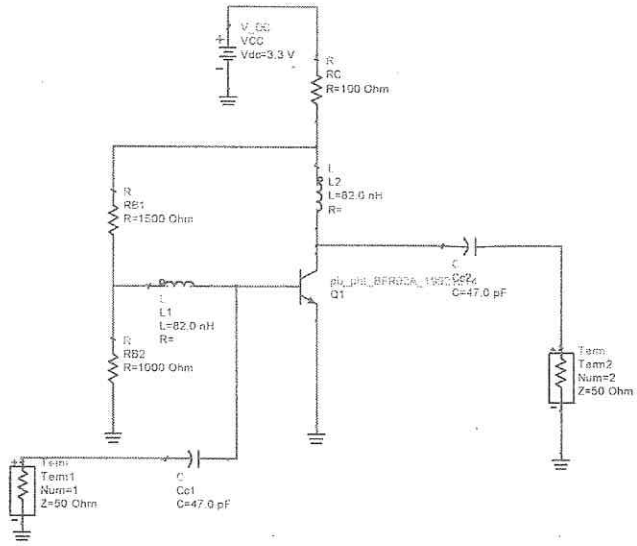
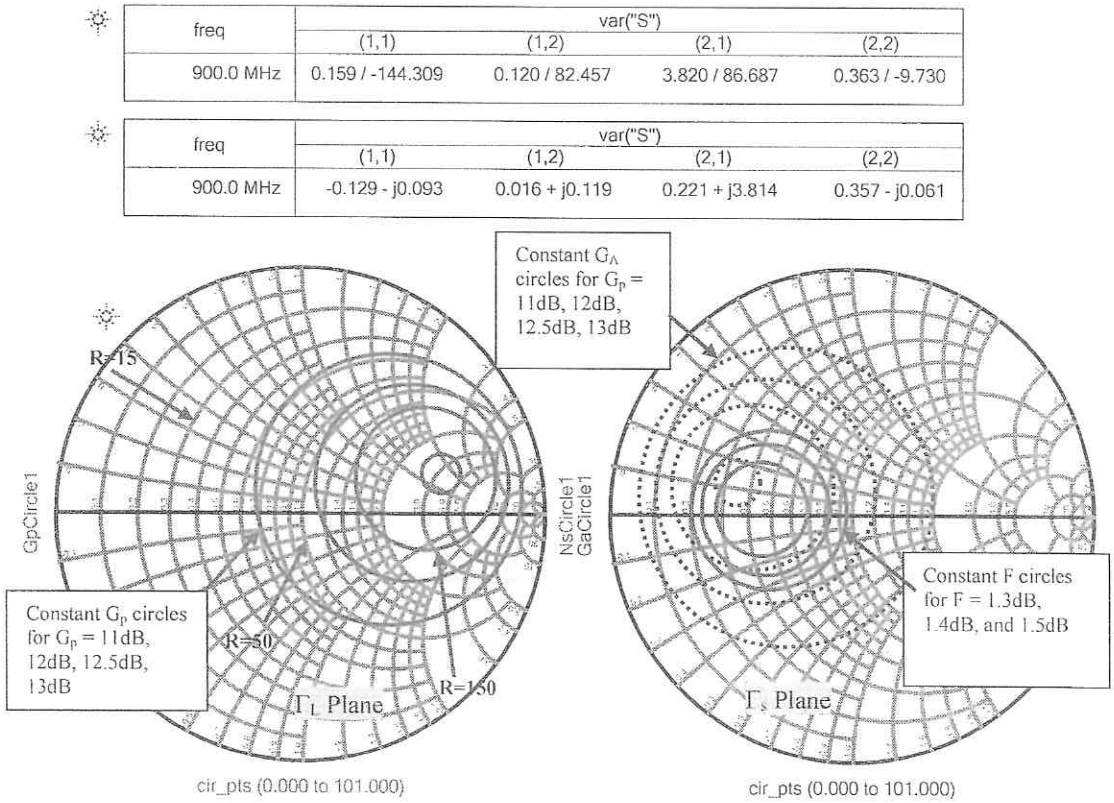


Figure Q2A – Amplifier schematic.



freq	var("S")			
	(1,1)	(1,2)	(2,1)	(2,2)
900.0 MHz	0.159 / -144.309	0.120 / 82.457	3.820 / 86.687	0.363 / -9.730

freq	var("S")			
	(1,1)	(1,2)	(2,1)	(2,2)
900.0 MHz	-0.129 - j0.093	0.016 + j0.119	0.221 + j3.814	0.357 - j0.061

Figure Q2B – Small-signal performance of the amplifier at 900 MHz.

Continued...

Question 3

(a) Explain why a class A or class AB amplifier needs to be operated near the gain compression point for maximum power efficiency.

[6 marks]

(b) A single-ended down-converting mixer is shown in Figure Q3A. The frequency of the RF and LO sources are 870 MHz and 820 MHz respectively. The simulated power spectrum at the load resistor R_L and RF input are shown in Figure Q3B (Harmonic Balance analysis is used to obtain the waveforms).

(i) Briefly explain how this circuit can produce frequency mixing effect.

(ii) Determine the IF frequency.

(iii) Calculate the LO-to-RF rejection and LO-to-IF rejection in decibel (dB).

(iv) Determine the conversion gain of the mixer.

(v) Suggest ONE approach each to increase the LO-to-RF and LO-to-IF rejection.

(vi) What would be the outcome if the available power of the LO source is decreased from +3 dBm to 0 dB?

[4 + 2 + 4 + 3 + 4 + 2 marks]

Continued...

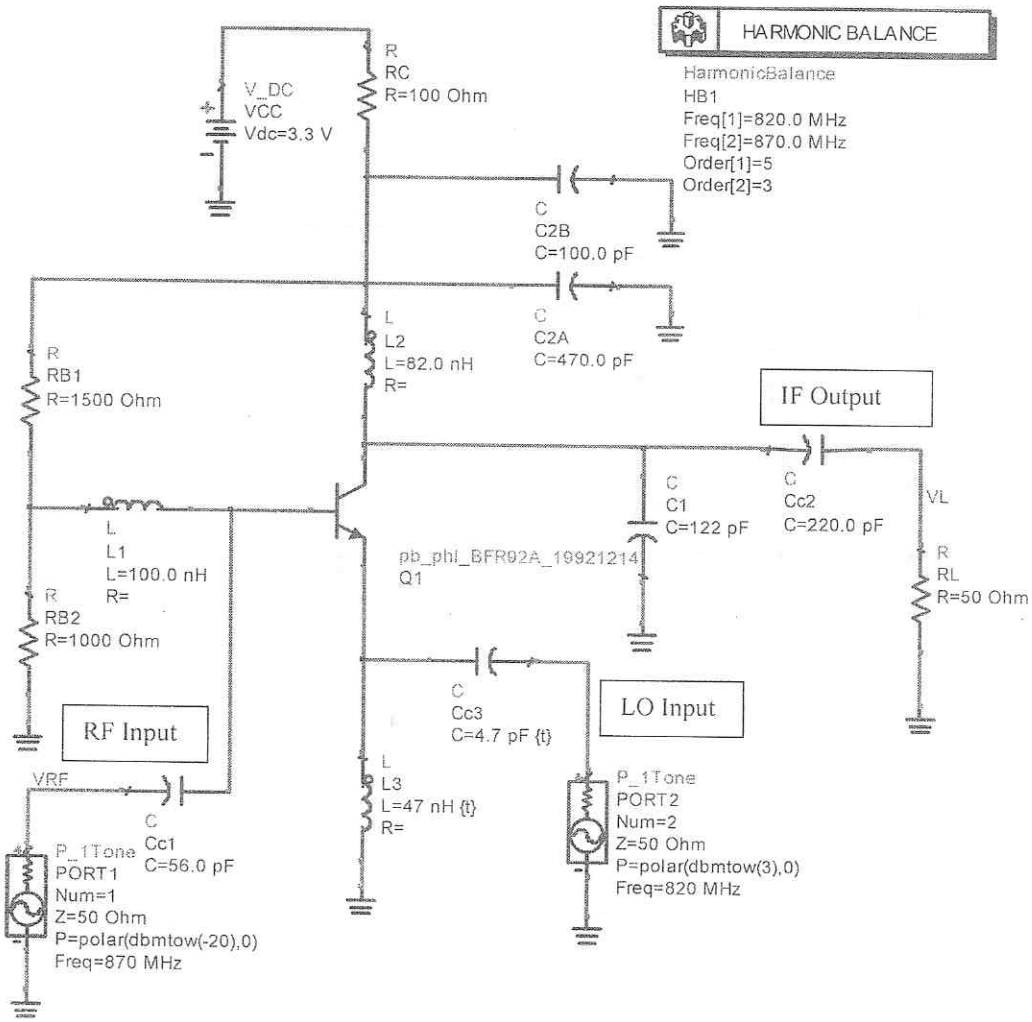


Figure Q3A – The single-ended mixer schematic.

Continued...

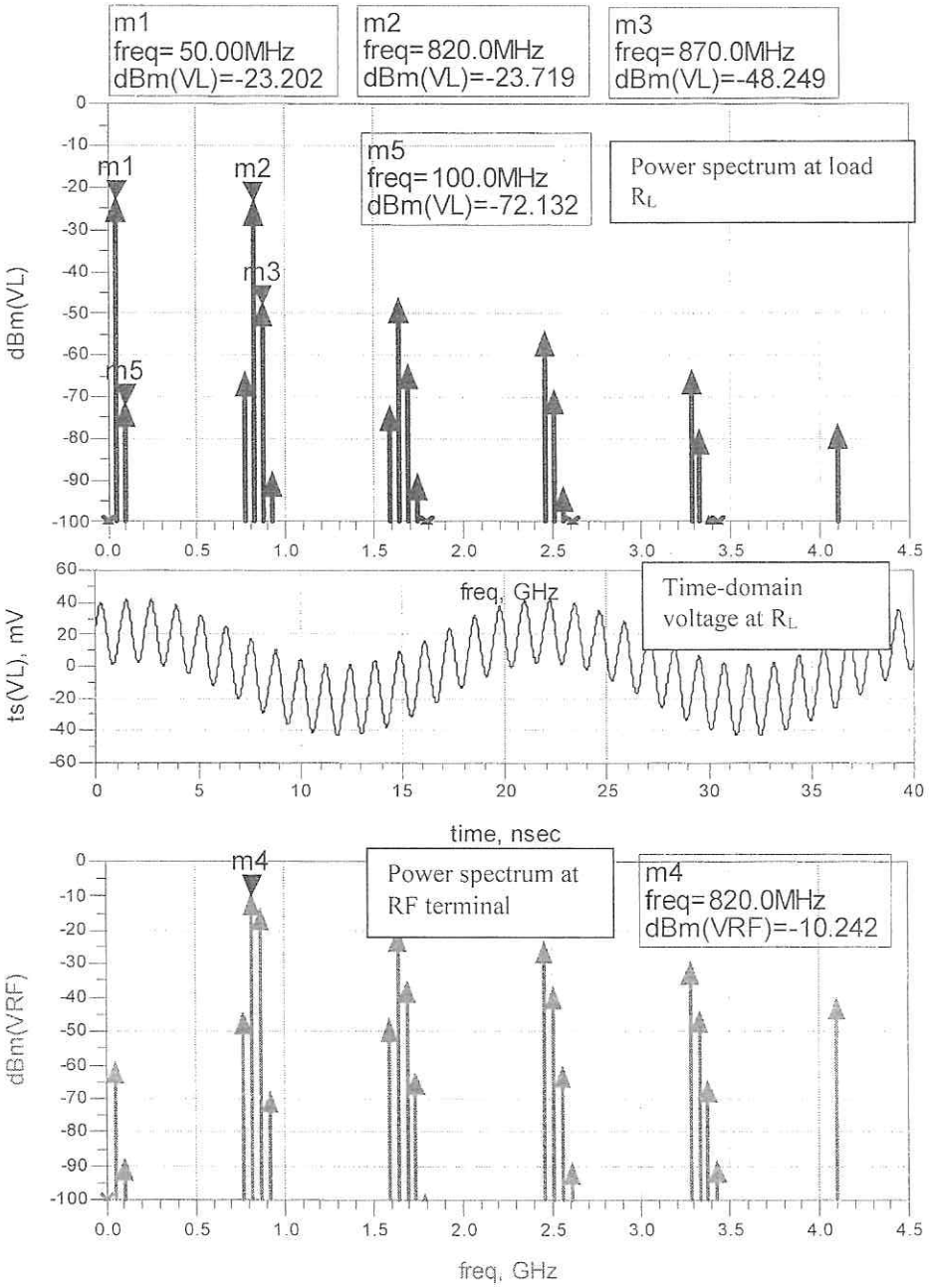


Figure Q3B – The output spectrum and time-domain waveforms of the mixer.

Continued...

Question 4

(a) A microwave engineering student designed a 700 MHz fixed frequency oscillator circuit, as shown in Figure Q4A. The equivalent series impedance looking into capacitor C_{C1} is also shown. He later discovered that the circuit cannot oscillate at all upon power up. Study the circuit carefully, and suggest what is wrong with the schematics and propose a remedy.

[7 marks]

(b) A prototype 2.3-2.6 GHz RF voltage controlled oscillator is shown in Figure Q4B. The circuit is constructed on 30 mils (about 0.8 mm) thick Rogers R4350 substrate. Explain

(i) The use of 30 mils thick R4350 instead of the popular 62 mils thick FR4 substrate.

(ii) The rationale of having the LDO (low drop-out) voltage regulator LP2985.

(iii) The use of high Q and precision (± 0.05 pF tolerance) capacitors for C_1, C_2 and C_{C1}.

(iv) The purpose of RC network R_1, R_2, C_1 and C_2.

(v) The purpose of RC network R_3 and C_8. Estimate the cutoff frequency of this network.

[5 + 3 + 3 + 3 + 4 marks]

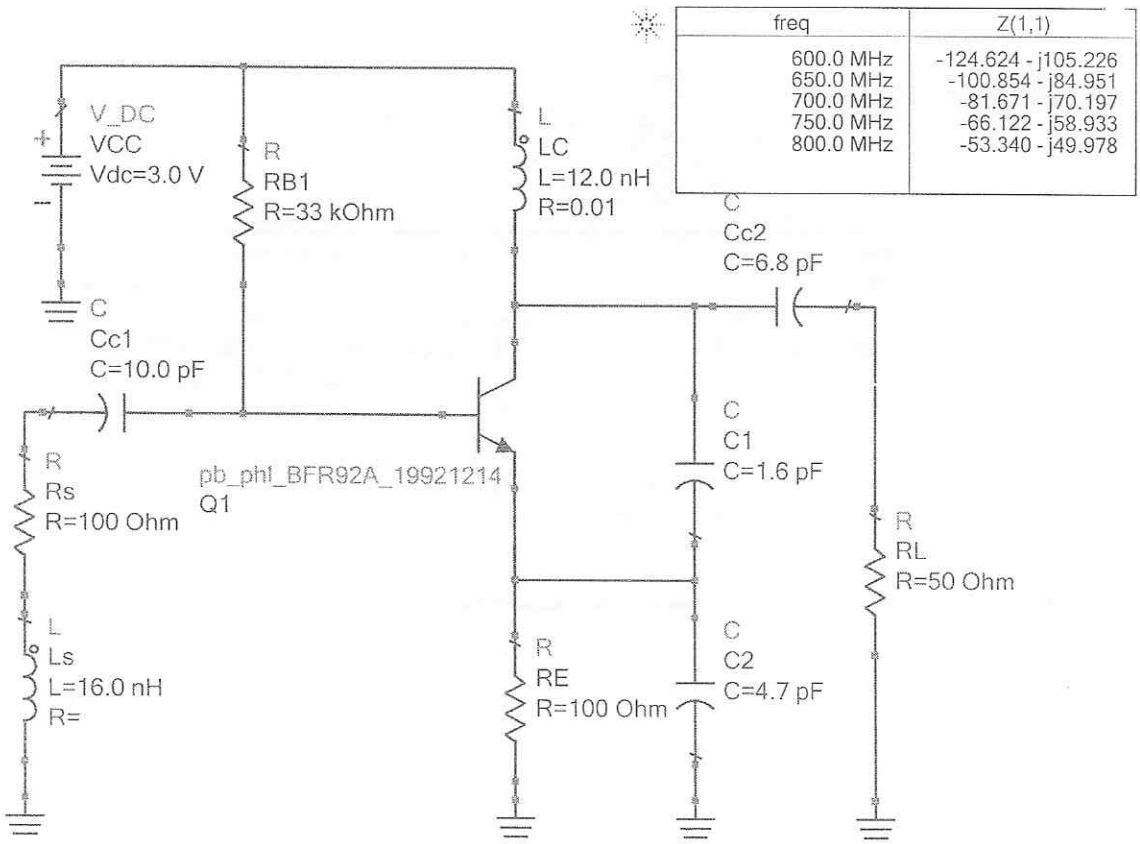


Figure Q4A – 700 MHz oscillator circuit.

Continued...

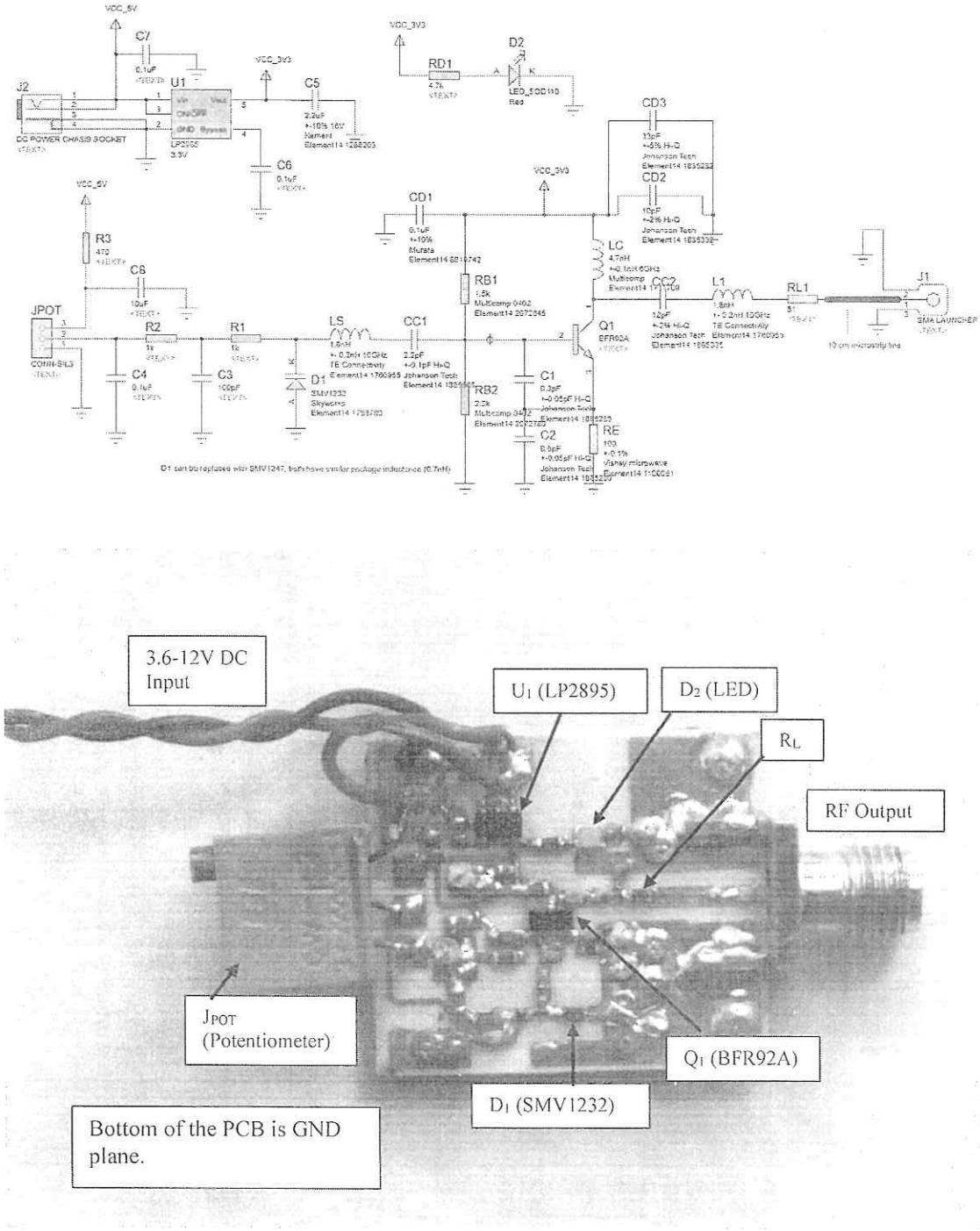


Figure Q4B – 2.3-2.6 GHz microwave VCO circuit and prototype.

Continued...

Appendix 1 – Extracts of Datasheets for RF Transistors

BFR520:

BFR520

NPN 9 GHz wideband transistor

Rev. 4 — 13 September 2011 Product data sheet

1. Product profile

1.1 General description

The BFR520 is an NPN silicon planar epitaxial transistor in a SOT23 plastic package.

1.2 Features and benefits

- High power gain
- Low noise figure
- High transition frequency
- Gold metallization ensures excellent reliability.

1.3 Applications

- RF front end wideband applications in the GHz range
  - Analog and digital cellular telephones
  - Cordless telephones (CT1, CT2, DECT, etc.)
  - Radar detectors
  - Pagers and satellite TV tuners (SATV)
  - Repeater amplifiers in fiber-optic systems.

1.4 Quick reference data

Table 1. Quick reference data

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_{CBO}	collector-base voltage			-	-	20	V
V_{CES}	collector-emitter voltage	$R_{BE} = 0\ \Omega$		-	-	15	V
I_C	collector current (DC)			-	-	70	mA
P_{tot}	total power dissipation	up to $T_{sp} = 97\ °C$	[1]	-	-	300	mW
h_{FE}	DC current gain	$I_C = 20$ mA; $V_{CE} = 6$ V		60	120	250	
C_{re}	feedback capacitance	$I_C = i_c = 0$ A; $V_{CB} = 6$ V; f = 1 MHz		-	0.4	-	pF
f_T	transition frequency	$I_C = 20$ mA; $V_{CE} = 6$ V; f = 1 GHz		-	9	-	GHz
G_{UM}	maximum unilateral power gain	$I_C = 20$ mA; $V_{CE} = 6$ V; $T_{amb} = 25\ °C$					
		f = 900 MHz		-	15	-	dB
		f = 2 GHz		-	9	-	dB

Continued...

Table 7. Characteristics ...*continued*
T_j = 25 °C unless otherwise specified.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
NF	noise figure	$\Gamma_s = \Gamma_{opt}$; V_{CE} = 6 V; T_{amb} = 25 °C					
		I_C = 5 mA; f = 900 MHz		-	1.1	1.6	dB
		I_C = 20 mA; f = 900 MHz		-	1.6	2.1	dB
		I_C = 5 mA; f = 2 GHz		-	1.9	-	dB
$P_{L(1dB)}$	output power at 1 dB gain compression	I_C = 20 mA; V_{CE} = 6 V; R_L = 50 Ω; T_{amb} = 25 °C; f = 900 MHz		-	17	-	dBm
ITO	third order intercept point		[2]	-	26	-	dBm

[1] G_{UM} is the maximum unilateral power gain, assuming s_{12} is zero and

$$G_{UM} = 10 \log \frac{|s_{21}|^2}{(1-|s_{11}|^2)(1-|s_{22}|^2)} dB.$$

[2] I_C = 20 mA; V_{CE} = 6 V; R_L = 50 Ω; T_{amb} = 25 °C; f_p = 900 MHz; f_q = 902 MHz.
Measured at $f_{(2p-q)}$ = 898 MHz and $f_{(2q-p)}$ = 904 MHz.

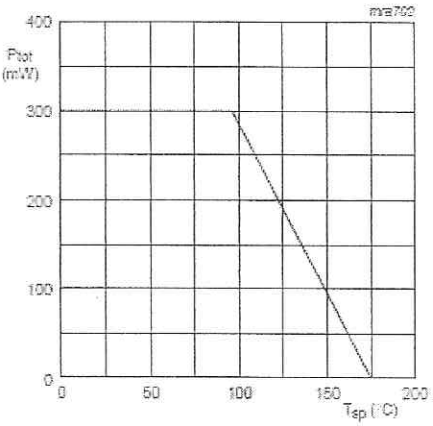
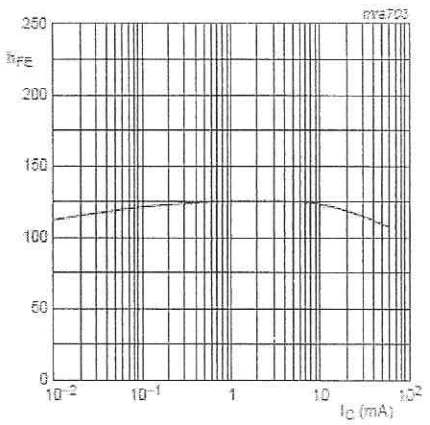


Fig 1. Power derating curve.



V_{CE} = 6 V.

Fig 2. DC current gain as a function of collector current.

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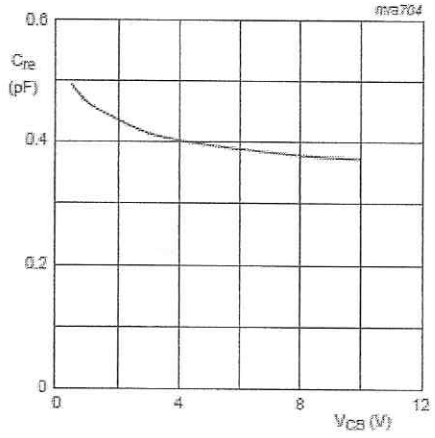
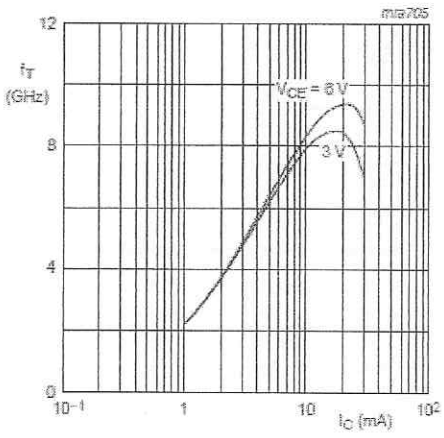


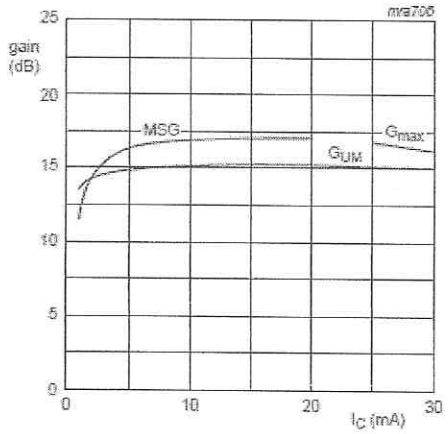
I_C = 0 A; f = 1 MHz.

Fig 3. Feedback capacitance as a function of collector-base voltage.



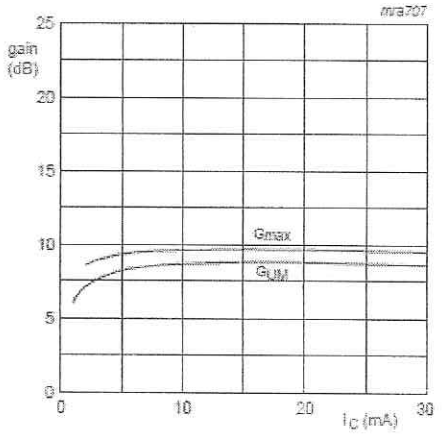
T_{amb} = 25 °C; f = 1 GHz.

Fig 4. Transition frequency as a function of collector current.



V_{CE} = 6 V; f = 900 MHz.

Fig 5. Gain as a function of collector current; f = 900 MHz.



V_{CE} = 6 V; f = 2 GHz.

Fig 6. Gain as a function of collector current; f = 2 GHz.

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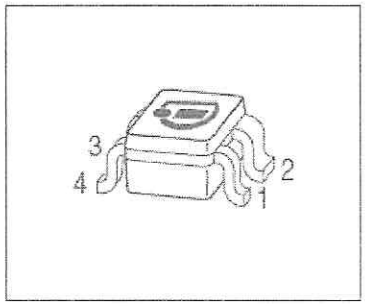
BFP420:

Infineon

BFP420

NPN Silicon RF Transistor



- For high gain low noise amplifiers
- For oscillators up to 10 GHz
- Noise figure F = 1.1 dB at 1.8 GHz
  outstanding G_{ms} = 21 dB at 1.8 GHz
- Transition frequency f_T = 25 GHz
- Gold metallization for high reliability
- SIEGET ® 25 GHz fT - Line
- Pb-free (RoHS compliant) package [1)]
- Qualified according AEC Q101

AEC Qualified RoHS

ESD (Electrostatic discharge) sensitive device, observe handling precaution!

Type	Marking	Pin Configuration						Package
BFP420	AMs	1=B	2=E	3=C	4=E	-	-	SOT343

Maximum Ratings

Parameter	Symbol	Value	Unit
Collector-emitter voltage	V_{CEO}		V
$T_A > 0$ °C		4.5	
$T_A \leq 0$ °C		4.1	
Collector-emitter voltage	V_{CES}	15	
Collector-base voltage	V_{CBO}	15	
Emitter-base voltage	V_{EBO}	1.5	
Collector current	I_C	35	mA
Base current	I_B	3	
Total power dissipation[2)] $T_S \leq 107$ °C	P_{tot}	160	mW
Junction temperature	T_j	150	°C
Ambient temperature	T_A	-65 ... 150	
Storage temperature	T_{stg}	-65 ... 150	

[1]Pb-containing package may be available upon special request
[2]T_S is measured on the collector lead at the soldering point to the pcb

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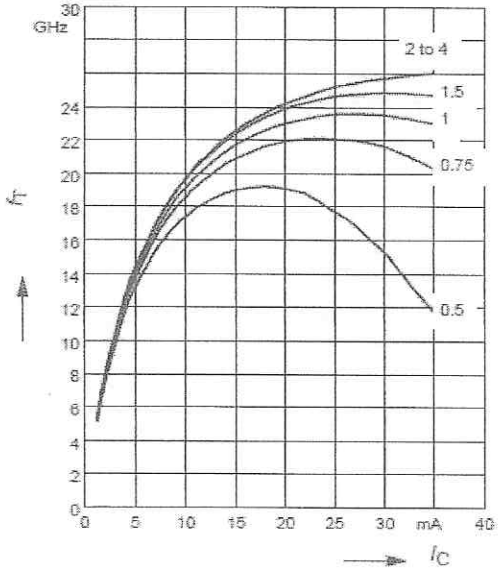
Transition frequency $f_T = f(I_C)$

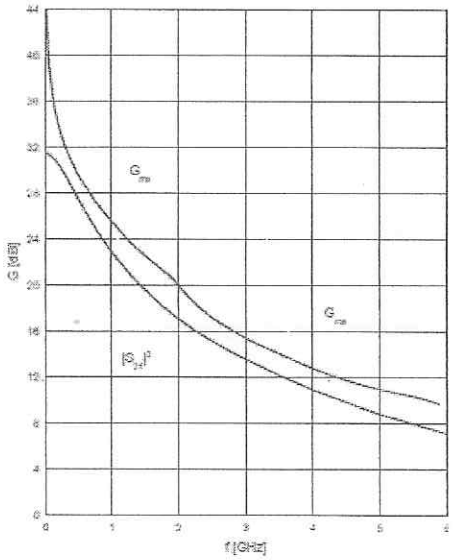
f = 2 GHz

V_{CE} = parameter in V



Power gain G_{ma}, G_{ms}, $|S_{21}|^2 = f(f)$

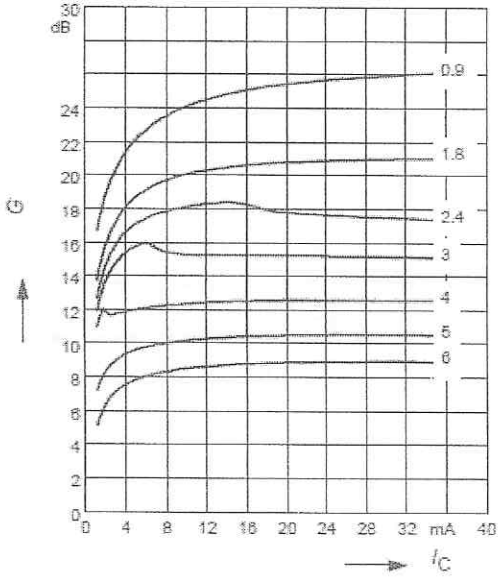
V_{CE} = 2 V, I_C = 20 mA



Power gain G_{ma}, $G_{ms} = f(I_C)$

V_{CE} = 2V

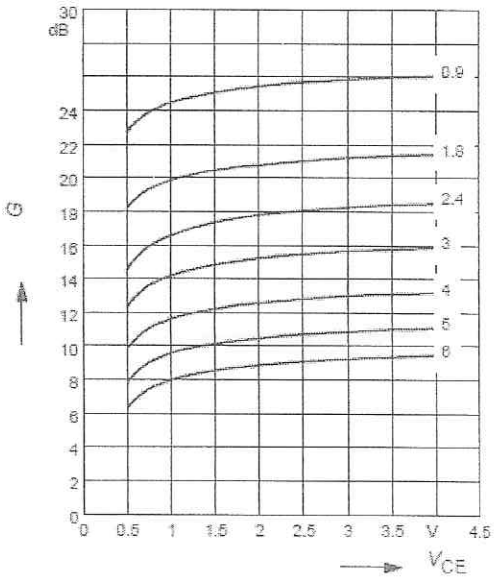
f = parameter in GHz



Power gain G_{ma}, $G_{ms} = f(V_{CE})$

I_C = 20 mA

f = parameter in GHz



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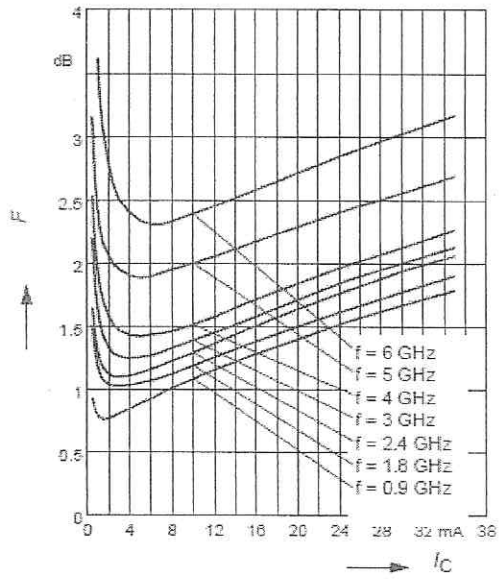
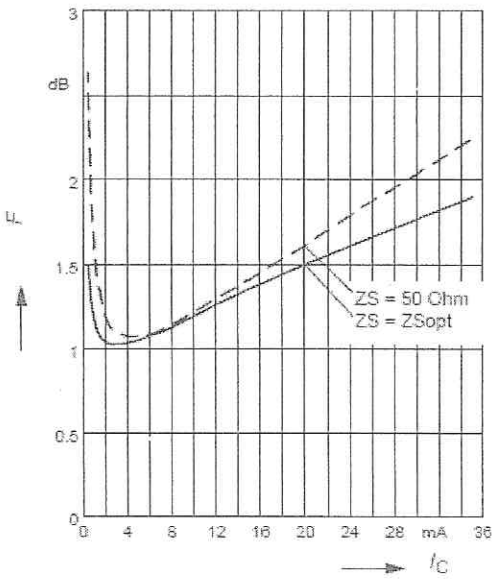
BFP420

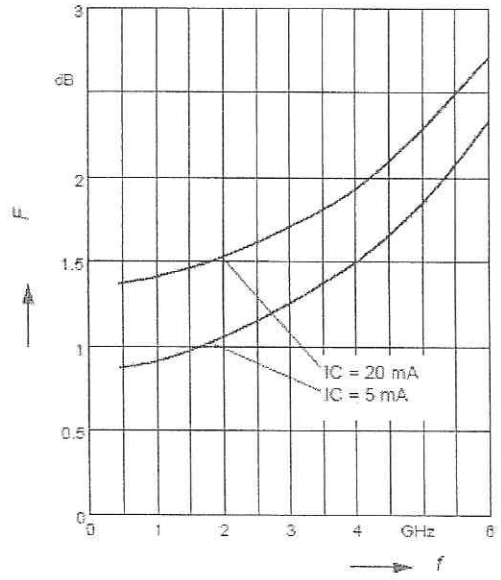
Noise figure $F = f(I_C)$
V_{CE} = 2 V, $Z_S = Z_{Sopt}$



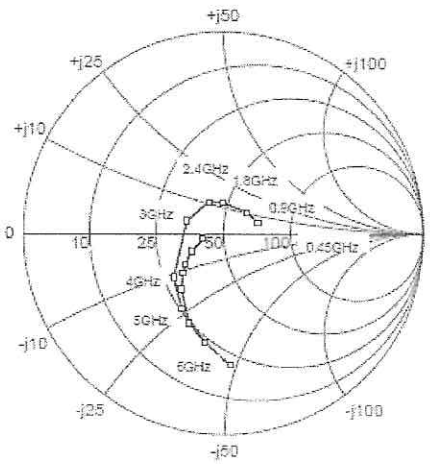
Noise figure $F = f(I_C)$
V_{CE} = 2 V, f = 1.8 GHz



Noise figure $F = f(f)$
V_{CE} = 2 V, $Z_S = Z_{Sopt}$



Source impedance for min. noise figure vs. frequency
V_{CE} = 2 V, I_C = 5 mA / 20 mA



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BFG425W:

NXP Semiconductors

Product specification

NPN 25 GHz wideband transistor

BFG425W

FEATURES

- Very high power gain
- Low noise figure
- High transition frequency
- Emitter is thermal lead
- Low feedback capacitance.

APPLICATIONS

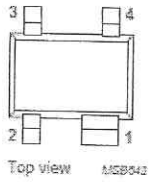
- RF front end
- Wideband applications, e.g. analog and digital cellular telephones, cordless telephones (PHS, DECT, etc.)
- Radar detectors
- Pagers
- Satellite television tuners (SATV)
- High frequency oscillators.

DESCRIPTION

NPN double polysilicon wideband transistor with buried layer for low voltage applications in a plastic, 4-pin dual-emitter SOT343R package.

PINNING

PIN	DESCRIPTION
1	emitter
2	base
3	emitter
4	collector



Marking code: P5*

* = - : made in Hong Kong
* = p : made in Hong Kong
* = t : made in Malaysia

Fig.1 Simplified outline SOT343R.

QUICK REFERENCE DATA

SYMBOL	PARAMETER	CONDITIONS	MIN.	TYP.	MAX.	UNIT
V_{CBO}	collector-base voltage	open emitter	–	–	10	V
V_{CEO}	collector-emitter voltage	open base	–	–	4.5	V
I_C	collector current (DC)		–	25	30	mA
P_{tot}	total power dissipation	$T_s \leq 103$ °C	–	–	135	mW
h_{FE}	DC current gain	I_C = 25 mA; V_{CE} = 2 V; T_j = 25 °C	50	80	120	
C_{re}	feedback capacitance	I_C = 0; V_{CB} = 2 V; f = 1 MHz	–	95	–	fF
f_T	transition frequency	I_C = 25 mA; V_{CE} = 2 V; f = 2 GHz; T_{amb} = 25 °C	–	25	–	GHz
G_{max}	maximum power gain	I_C = 25 mA; V_{CE} = 2 V; f = 2 GHz; T_{amb} = 25 °C	–	20	–	dB
F	noise figure	I_C = 2 mA; V_{CE} = 2 V; f = 2 GHz; $\Gamma_S = \Gamma_{opt}$	–	1.2	–	dB

CAUTION
This product is supplied in anti-static packing to prevent damage caused by electrostatic discharge during transport and handling.

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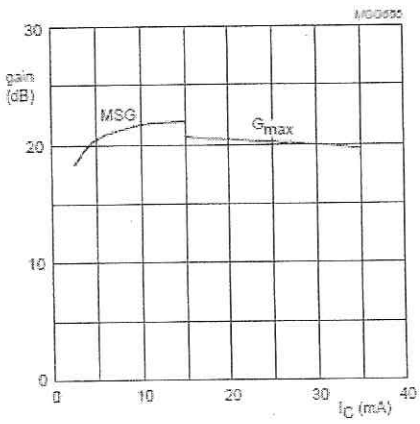
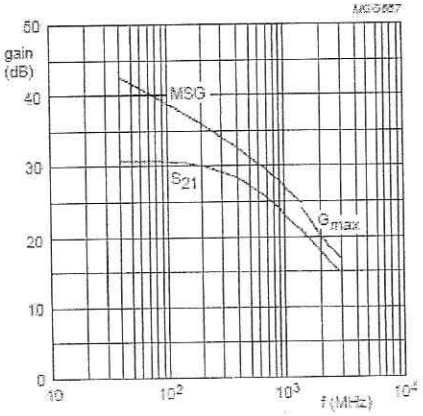


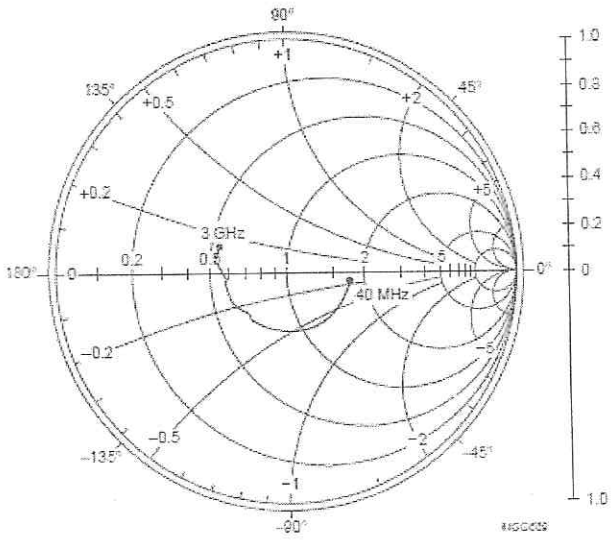
V_{CE} = 2 V; f = 2 GHz.

Fig.7 Gain as a function of collector current; typical values.



I_C = 25 mA; V_{CE} = 2 V.

Fig.8 Gain as a function of frequency; typical values.



I_C = 25 mA; V_{CE} = 2 V; Z_o = 50 Ω.

Fig.9 Common emitter input reflection coefficient (S_{11}); typical values.

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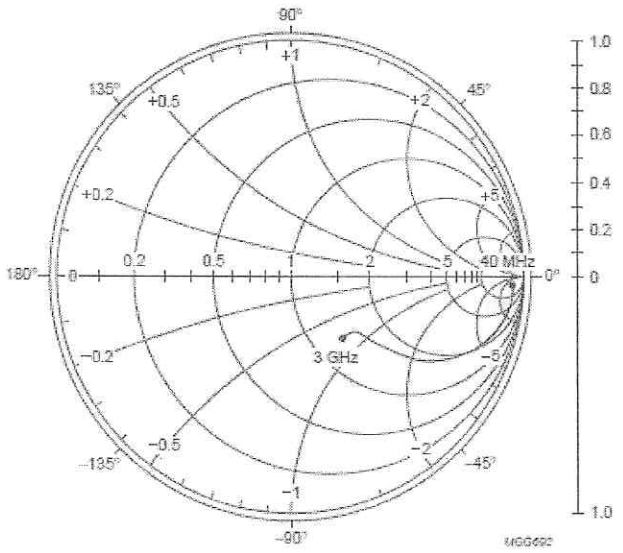


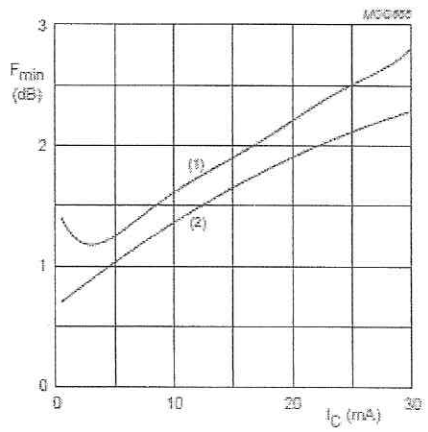
I_C = 25 mA; V_{CE} = 2 V; Z_o = 50 Ω.

Fig.12 Common emitter output reflection coefficient (S_{22}); typical values.

Noise data

V_{CE} = 2 V; typical values.

f (MHz)	I_C (mA)	F_{min} (dB)	Γ_{mag}	Γ_{angle}	r_n (Ω)
900	1	0.7	0.67	19.1	0.40
	2	0.8	0.48	17.8	0.27
	4	1	0.28	11.7	0.24
	10	1.4	0.02	−63.9	0.19
	15	1.6	0.11	−162.4	0.18
	20	1.9	0.19	−165.5	0.18
	25	2.1	0.25	−166.3	0.19
	30	2.3	0.29	−166.5	0.19
2000	1	1.3	0.56	57.5	0.36
	2	1.2	0.43	57.2	0.25
	4	1.2	0.22	60.8	0.18
	10	1.6	0.06	137.4	0.19
	15	1.9	0.13	−162.1	0.20
	20	2.2	0.17	−155.5	0.20
	25	2.5	0.22	−152.2	0.21
	30	2.8	0.27	−150.8	0.25



(1) V_{CE} = 2 V; f = 2 GHz.
(2) V_{CE} = 2 V; f = 900 MHz.

Fig.13 Minimum noise figure as a function of the collector current; typical values.

Continued...

Appendix 2 – Useful Formulae

Gain Expressions:

$$\Gamma_1 = \frac{S_{11} - D\Gamma_L}{1 - S_{22}\Gamma_L}$$

$$\Gamma_2 = \frac{S_{22} - D\Gamma_S}{1 - S_{11}\Gamma_S}$$

$$G_T = \frac{\left(1-|\Gamma_L|^2\right)|S_{21}|^2\left(1-|\Gamma_S|^2\right)}{|1-S_{22}\Gamma_L|^2|1-\Gamma_1\Gamma_S|^2}$$

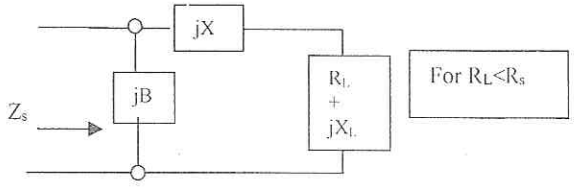
$$G_A = \frac{\left(1-|\Gamma_S|^2\right)|S_{21}|^2}{|1-S_{11}\Gamma_S|^2\left(1-|\Gamma_2|^2\right)}$$

$$G_P = \frac{|S_{21}|^2\left(1-|\Gamma_L|^2\right)}{|1-S_{22}\Gamma_L|^2\left(1-|\Gamma_1|^2\right)}$$

Two Elements Impedance Matching:

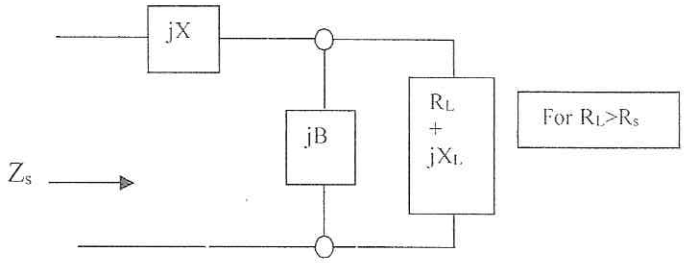
$$X = -X_L \pm \sqrt{R_L(R_S - R_L) + \frac{R_L}{R_S}X_S^2}$$

$$B = \frac{R_S - R_L}{R_S X_L + R_L X_S + R_S X}$$



$$X = X_S \pm \sqrt{R_S(R_L - R_S) + \frac{R_S}{R_L}X_L^2}$$

$$B = \frac{R_S - R_L}{R_S X_L + R_L X_S - R_L X}$$



Stability Circles:

$$T_{SSC} = \frac{\left(S_{11} - DS_{22}^*\right)^*}{|S_{11}|^2 - |D|^2} \qquad R_{SSC} = \left|\frac{S_{12}S_{21}}{|S_{11}|^2 - |D|^2}\right|$$

$$T_{LSC} = \frac{\left(S_{22} - DS_{11}^*\right)^*}{|S_{22}|^2 - |D|^2} \qquad R_{LSC} = \left|\frac{S_{12}S_{21}}{|S_{22}|^2 - |D|^2}\right|$$

Stability Factor:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |D|^2}{2|S_{12}S_{21}|} > 1$$

$$|D| < 1$$

Continued...

Simultaneous Conjugate Match Design:

$$G_{P(\max)} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right)$$

$$\Gamma_{Sm} = \frac{1}{2B_1}\left(A_1 - \left(A_1{}^2 - 4|B_1|^2\right)^{\frac{1}{2}}\right) \qquad \Gamma_{Lm} = \frac{1}{2B_2}\left(A_2 - \left(A_2{}^2 - 4|B_2|^2\right)^{\frac{1}{2}}\right)$$

$$A_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |D|^2 \qquad A_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |D|^2$$

$$B_1 = S_{11} - DS_{22}^* \qquad B_2 = S_{22} - DS_{11}^*$$

Design for constant Power Gain:

$$C_2 = S_{22} - DS_{11}{}^*$$

$$G_{P(MSG)} = \frac{|S_{21}|}{|S_{12}|} \quad g_2 = \frac{G_P}{|S_{21}|^2}$$

$$T_{G_P} = \frac{-g_2\,\mathrm{Re}(C_2)}{-1 - |S_{22}|^2 g_2 + |D|^2 g_2} + j\frac{g_2\,\mathrm{Im}(C_2)}{-1 - |S_{22}|^2 g_2 + |D|^2 g_2}$$

$$R_{G_P} = \frac{\sqrt{1 - 2K|S_{12}S_{21}|g_2 + |S_{12}S_{21}|^2 g_2{}^2}}{\left|-1 - |S_{22}|^2 g_2 + |D|^2 g_2\right|}$$

Noise Figure Expressions:

$$F = F_m + \frac{G_i}{R_s}|Z_S - Z_m|^2 = F_m + \frac{R_e}{G_s}|Y_S - Y_m|^2 \qquad G_i = \frac{R_e}{|Z_m|^2}$$

$$N_i = \frac{Z_o(F - F_m)|1 + \Gamma_m|^2}{4R_e} = \frac{(F - F_m)|1 + \Gamma_m|^2}{4Z_o G_i}$$

$$T_{Fcenter} = \frac{\Gamma_m}{1 + N_i} \qquad R_{Frad} = \frac{\sqrt{N_i^2 + N_i\left(1 - |\Gamma_m|^2\right)}}{1 + N_i}$$

For cascaded system consisting of stage 1 and stage 2, let:
F_1, F_2 = noise figure of stage 1 and stage 2 respectively.
G_{p1} = Power gain of stage 1.
G_{A1} = Available power gain of stage 1.
M_1 = mismatch factor at input of stage 1.
M_2 = mismatch factor between stage 1 and stage 2.

$$F = F_1 + (F_2 - 1)\frac{M_2}{M_1 G_{p1}} = F_1 + \frac{(F_2 - 1)}{G_{A1}}$$

End of Paper.